The Perception of Ultrasonic Square Reductions of Friction with Variable Sharpness and Duration

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Abstract—The human perception of square ultrasonic modulation of the finger-surface friction was investigated during active tactile exploration by using short frictional cues of varying duration and sharpness. In a first experiment, we asked participants to discriminate the transition time and duration of short square ultrasonic reductions of friction. They proved very sensitive to discriminate millisecond differences in these two parameters with the average psychophysical thresholds being 2.3-2.4 ms for both parameters. A second experiment focused on the perception of square friction reductions with variable transition times and durations. We found that for durations of the stimulation larger than 90 ms, participants often perceived three or four edges when only two stimulations were presented while they consistently felt two edges for signals shorter than 50 ms. A subsequent analysis of the contact forces induced by these ultrasonic stimulations during slow and fast active exploration showed that two identical consecutive ultrasonic pulses can induce significantly different frictional dynamics especially during fast motion of the finger. These results confirm the human sensitivity to transient frictional cues and suggest that the human perception of square reductions of friction can depend on their sharpness and duration as well as on the speed of exploration.

Index Terms—short ultrasonic vibration, friction perception, psychophysics, finger-surface mechanics, edge detection, force feedback.

1 Introduction

The development of natural haptic feedback in mobile devices such as smartphones and tablets as well as in virtual environments has been rapidly growing in the recent years. One such feedback technology, vibrotactile stimulation, is already incorporated on most platforms but only conveys vibratory signals to the hand and fingers of users. To improve upon this feedback method, solutions to modulate the finger-surface friction have been proposed in recent years. One such technique is electrovibration, which creates an electrostatic attraction between the finger and the actuated surface and increases the finger-surface friction [1], [2]. Another technique, ultrasonic lubrication [3] is able to reduce the finger-surface friction by generating a squeeze film effect and an intermittent contact with the surface [4]–[6] either through a stationary wave on the whole surface or through evanescent waves within a precise location [7]. These technologies have very different means of action but they nevertheless induce a change in the dynamic friction between the finger and the tactile plate, which is similarly perceived [8].

Until recently, studies were primarily focusing on the threshold for perceiving the changes in the intensity of the frictional force induced by either ultrasonic lubrication [9]–[11] or electrovibration [12]. However, the frictional gradient of friction-based textures is perceptually salient [13] and the rate of change in the lateral force has been shown to affect the perceived intensity of periodic modulations of friction with the same amplitude [14] as well as the perceptual threshold for rising and falling frictional steps [15]. The duration of a tactile signal can also have strong perceptual effects. The dependency between the perceived intensity and duration for short stimuli is well-known in vision and audition [16], [17] and has also been reported in the tactile modality [18]. Moreover, duration was found to affect tactile perception by doubling the number of perceived tactile features for larger time lengths of the signal [19].

Hence, understanding how the waveform properties of frictional signals impact perception is a major challenge for haptic rendering on friction-based tactile displays. For example, recent research has shown that primitive geometric shapes do not naturally associate with the frictional pattern created by electrovibration of the surface if participants are not provided with guidance about the context [20]. A following study proposed a gradient-based algorithm for rendering 3D haptic shapes with friction modulation, in which the sharpest edges are additionally emphasized by a transient change in the grain of the frictional texture [21]. These results and developments emphasize that a better knowledge of the tactile perception of sharpness, duration and transient changes in frictional signals is important for improving our understanding on how to render friction-based textures, objects and shapes that feel natural to the users.

In our study, we specifically investigate the human perception of transient stepwise modulation of the lateral force to understand how sharpness and duration influence the human perception of short frictional cues. In this experimental design, square reduction of friction consists in a stepwise increase of the ultrasonic amplitude generated by the tactile device followed by a stepwise return to the absence of ultrasonic vibration. In a first experiment, we

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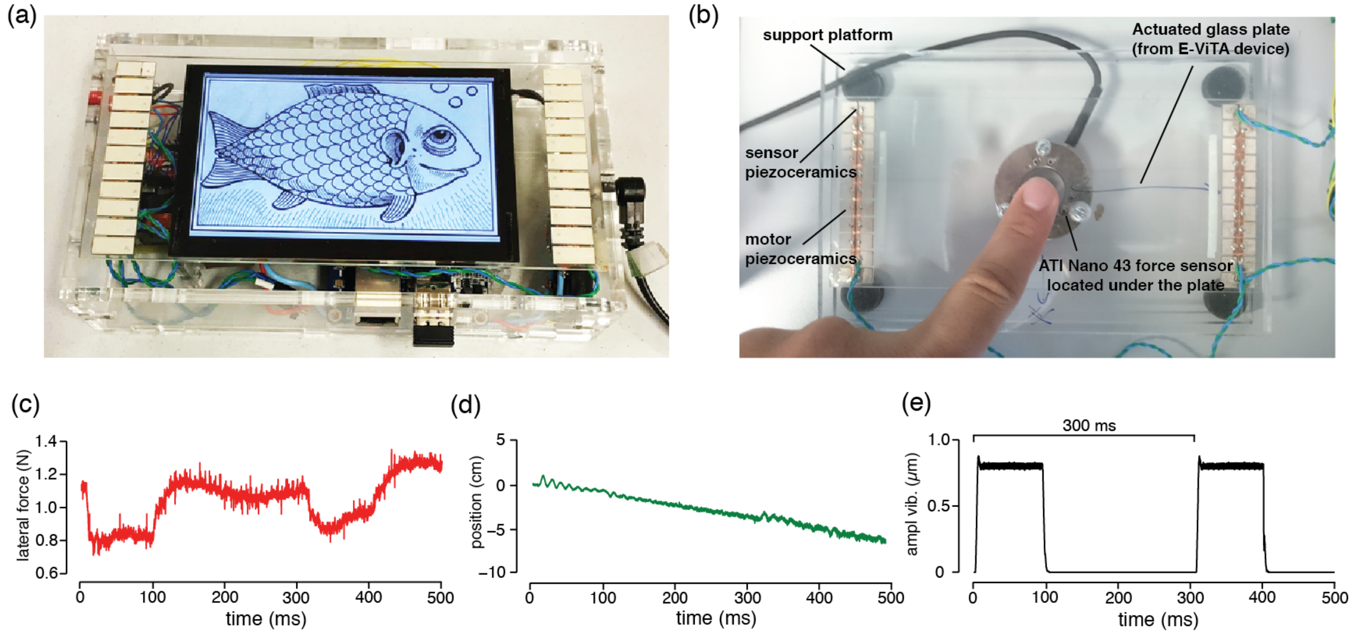

Fig. 1. (a) The visuo-haptic ultrasonic device E-ViTa, which was used to deliver ultrasonic square stimulations in the psychophysical experiments. (b) The glass plate from the E-ViTa device was mounted on a force transducer based on a 3-axis ATI Nano43 force sensor (c) In experiment 3, the recording of the amplitude of ultrasonic vibration and of the interfacial forces enabled the analysis of the precise contact mechanics induced by the ultrasonic signals. (d) The center of pressure of the fingertip hence the speed of exploration could be computed out of the forces and torques recorded in experiment 3. (e) In all three experiments, two consecutive identical square ultrasonic pulses were delivered when the finger reached the middle of the glass plate.

quantitatively investigate two parameters related to the perception of square waves: the *transition time*, which is the time needed to reach the desired amplitude of ultrasonic vibration and recover from it, and the *duration* of the uniform reduction of friction. We evaluated in a second experiment the subjective perception of consecutive square stimulations in order to estimate the conditions for which participants felt the square signal as two transient changes in friction rather than one percept. In a third experiment, we related the obtained psychophysical results for perceiving square reductions of friction to precise measurements of the elicited contact forces by playing ultrasonic patterns, very similar to those generated in experiment 2, while simultaneously recording the interfacial forces. We could therefore study the actual frictional signals induced by the ultrasonic patterns. We performed the experiment in two speed conditions to investigate the possible influence of exploratory speed on the induced frictional changes. On the basis of previous research, we expect humans to be highly sensitive to changes in the sharpness and duration of the frictional modulation. Moreover, the transient stepwise changes are probably more salient than the stabilized interval of lower friction and they should be perceived separately for larger durations of the signal. The speed of exploration is also expected to have a significant impact on the mechanical changes induced by the ultrasonic signal as in [11], [15].

2 Related work

Our study relates to a scientific effort that aims at understanding how humans perceive textures and shapes and at creating a realistic rendering of these through friction modulation on tactile displays. Friction modulation is a promising technique for creating realistic haptic feedback since it is well-known that the interfacial forces during touch play a key role in our perception of geometric features [22] and that the perception of edges depends on the shear strains induced by the resulting compression of the skin [23]. In addition, the finger-surface friction has an essential role in the human tactile perception of materials [24], [25]. Therefore, to implement realistic shapes and textures, it is essential to understand which components of the frictional signal are critical for tactile sensation and how to scale their intensities according to the dynamics of the interaction. Such an approach has been undertaken by a recent study on the finger-surface forces elicited by geometric features of different sizes and shapes. Its results showed that bumps and upward steps elicit frictional modulations that can be modelled based on the surface shape and the contact mechanics of the finger and therefore implemented in haptic displays [26].

The mechanisms of human sensing of frictional cues have been used for the development of several approaches aiming at rendering virtual tactile features on friction-based tactile displays. Promising rendering of bumps and holes has been implemented by mapping the shape geometry to the frictional force [20], [21], [27]. Important perceptual dimensions such as the perceived roughness [28], the pitch [29], or the pleasantness [30] of the signal can also be modulated by changing the waveform and frequency of the stimulation and the perception of frictional signals can be additionally modulated by a masking background noise [31]. Data-driven rendering of textures is also possible by replaying the acceleration or force signals elicited during tactile exploration of the natural textures [32], [33]. In order to adapt the replay of the texture to the tactile behaviour of the user, this technique has been further developed by coupling the recorded signal with neural network processing to account for the scanning speed and normal force [34]. Another suggested strategy for rendering textures is the coupling between frictional modulation and vibrotactile signal to mimic more closely the force and vibrotactile components of natural materials [35].

Beyond the rendering of textures and shapes, the applications for controlled friction modulation are becoming more diverse including new techniques for button-click rendering [36], [37] or haptic enrichment of musical experiences [38]. It is therefore essential to continue extending our understanding of the parameters mediating subjective perception of frictional signals in order to develop novel and more realistic types of haptic feedback.

3 General experimental procedure

3.1 Experimental apparatus

We first used an ultrasonic device with high temporal resolution and controlled amplitude of ultrasonic vibration [39] to investigate perception of short ultrasonic square reductions. This system includes both visual and haptic feedback (Fig. 1a). Finger touch position is directly acquired using a capacitive touch screen. Computation and control of the experiment is separated in two parts: a high level signal using the banana pi (Shenzhen LeMaker Technology Co. Ltd, China) single board computer featuring a 1 GHz ARM Cortex-A7 dual-core CPU with 1 GB of RAM. A low Level signal generation is implemented in a separate DSP microcontroller (STM32F4, STMicroelectronics, France) running at 164MHz. In this setup High level computing refers to the display of the instruction to the user, selection of the haptic signal commands and storage of the results. The signal generation microcontroller for its part applies commands from the board computer to create the necessary waveforms for the friction modulation. The communication between the microcontroller and the single board PC is provided by an SPI bus working at 10 kHz. In order to ensure the fastest amplitude transition time in this study, an external amplifier is used to drive the piezoceramic motors as in [40].

The single board computer is connected to a 5 inches flat capacitive touch screen (Banana-LCD-5"-TS, Marel, China) providing the finger position input and display output, where the sampling frequency of the finger position is 62 Hz. This LCD display gives visual confirmation of the experiment goals during the measures. A second visual system using a computer screen is used to display comfortably the controls of the experiments to each participant. The ultrasonic vibrating plate implemented in the device is specifically designed to provide the best modulation bandwidth. The glass plate measures 154x81x1.6 mm and resonates at 60750 Hz, where the half wavelength of the vibration mode is 8 mm. 22 piezoceramics, 14x6x0.5 mm, are mounted at the side of the plate along the extremum of deformation, 20 used as motors and 2 as vibration sensors. These two sensor piezoceramics enabled the device to monitor and adapt the amplitude of vibration to the desired level through a 10 kHz closed-loop. The output of the sensor piezoceramics was calibrated prior to the experiments with a laser doppler vibrometer (OFV 505, Polytec, Germany),

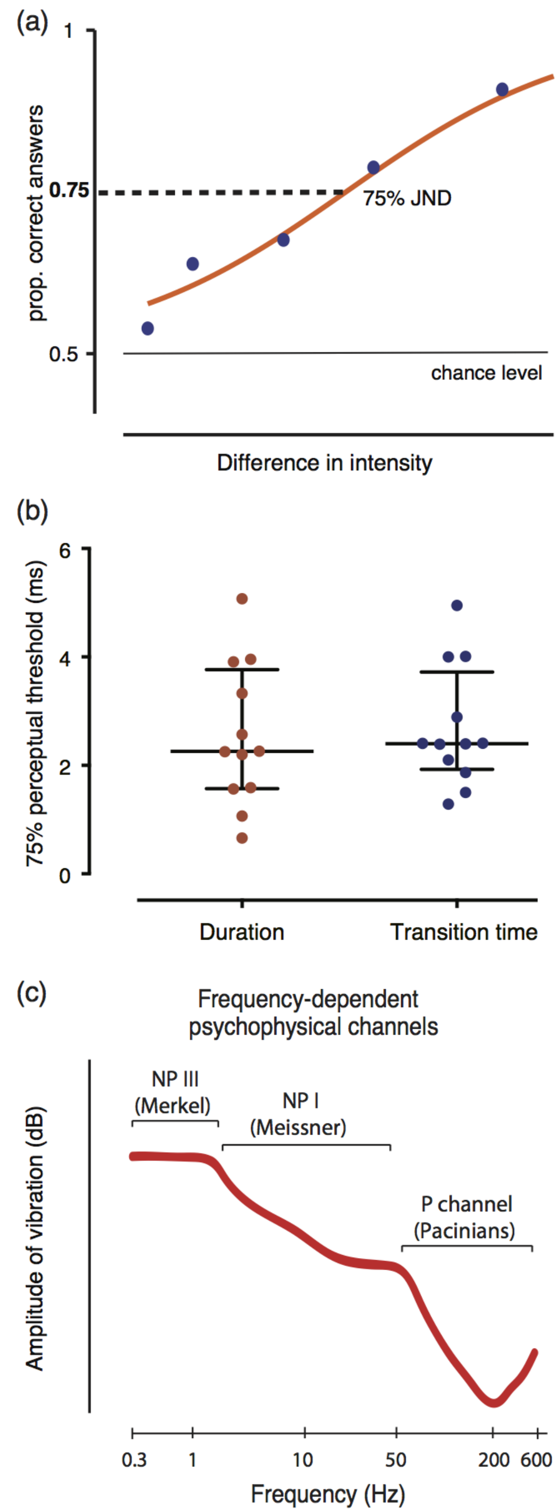

Fig. 2. (a) Example of a psychometric function fitted to psychophysical data. The 75% jnd is interpolated from the fitted curve. (b) Median 75% just noticeable differences for the duration and transition time of the square friction reductions (median $\pm$ IQR). The data points represent the computed individual thresholds. (c) Combined frequency-dependent threshold of the channels mediating tactile perception. Adapted from [14], [42].

which measured the vibration amplitude at several locations of the actuated plate. The transition time of the ultrasonic square stimulations is always defined as the necessary time interval for the vibration amplitude to vary between 10% to 90% of its maximum value.

We further developed a novel experimental set-up in order to record the interfacial forces underlying these stimulations and relate them to the psychophysical performance of the participants. To that end, the glass plate of the E-ViTA device used for the first two experiments was mounted on an ATI Nano43 3-axis force sensor (ATI, USA) (Fig. 1b) and connected to a ADECE-HAP-1200 amplifier. Two dedicated piezoceramics acted as sensors and recorded online the vibrations of the plate. The acquisition of the interfacial forces (Fig. 1c) and the torques was made at 3 kHz sampling frequency by using dedicated ATI electronics. The acquisitions were performed by sending MATLAB commands to a custom-made programmable electronic board, which was driving the piezoelectric actuators of the glass plate. The torques and forces were also used to compute the fingertips center of pressure, which enabled us to estimate the speed of exploration deployed during a given trial (Fig. 1d).

3.2 Ultrasonic stimulations

In all experiments, the ultrasonic stimulations consisted in two identical consecutive square friction reductions delivered with 300 ms interval (Fig. 1e). The stabilized ultrasonic amplitude was set at 1.25 μm in the first two experiment and 800 nm in experiment 3. The choice of two consecutive presentations of an identical signal as in [10] was made to enable a more reliable psychometric analysis in experiment 1 as well as to provide more options for the counting task performed in experiment 2. In all experiments, the movement was performed perpendicularly to the nodal lines of the ultrasonic device. The stimuli were presented while the finger was sliding on the surface at the precise time intervals described above. The surface of the ultrasonic device was cleaned after each experimental block with commercial screen cleaner.

3.3 Statistical and psychometric analyses

The decision to use parametric or non-parametric statistical methods on a given data sample was motivated by the D'Agostino and Pearson omnibus normality test, which we performed on all analysed samples using GraphPad Prism software. The 75% just noticeable difference (JND), which is commonly defined as the difference between the reference and a comparison stimulus that is correctly perceived in 75% of the trials, was computed by fitting a logistic psychometric function to the proportion of correct responses related to the increasing values of the investigated parameters. The psychometric fitting were performed using the dedicated functions of PALAMEDES toolbox based on maximum-likelihood method [41].

4 Experiment 1: perceptual limits of sharpness and duration

4.1 Participants

Twelve participants aged between 25 and 40 (2 females) took part in experiment 1. During the psychophysical experiments, participants were wearing active noise-canceling headphones (Quiet Comfort 25, Bose, USA) to prevent potential interference from auditory cues. All reported experiments conformed to the principles of the Declaration of Helsinki and were performed in accordance with relevant guidelines and regulations.

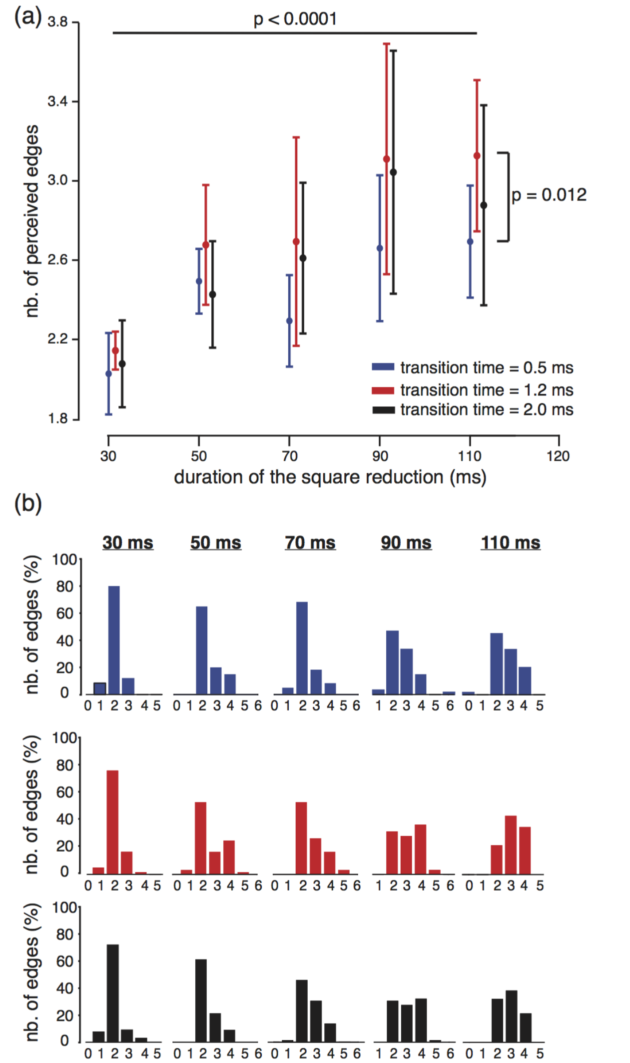

Fig. 3. (a) The average number of perceived edges per trial plotted against the duration of the signal for each of the three tested transition times (0.5 ms, 1.2 ms and 2 ms). The error bars represent the standard deviation across participants. (b) The average percentage of each possible answer (from 0 to 6) across participants plotted for all the possible durations and the three tested transition times (0.5 ms, 1.2 ms and 2.0 ms). The perceived number of edges is predominantly two for 30 ms of duration while it is uniformly distributed across 2,3 and 4 for the largest duration.

4.2 Materials and methods

Experiment 1 consisted in a two alternatives forced-choice task (2AFC) in which the participants had to compare varying ultrasonic square signals to a reference signal either in terms of sharpness or duration. The stimuli were chosen as sharp and short as possible because perception is mostly constrained by the minimal physical difference that can be resolved by the bandwidth of the tactile receptors. For vibrotactile stimuli, the sensitivity to tactile signal is bounded

TABLE 1
Average number of perceived edges for the extremal durations depending on transition time.

	transition time		
duration	**0.5 ms**	**1.2 ms**	**2.0 ms**
30 ms	2.03 ± 0.21	2.15 ± 0.10	2.08 ± 0.22
110 ms	2.70 ± 0.28	3.13 ± 0.38	2.88 ± 0.50

by the fast decreasing sensitivity of the mechanoreceptors between 400 Hz and 1000 Hz [42], [43] and this bandwidth is also valid for friction modulation [14]. In the sharpness task, participants had to pick the sharper out of two proposed stimulations, which they could explore up to three times before answering. One of the two stimuli, randomly presented first or second had always a 0.3 ms transition time and 10 ms duration while the comparison stimulus was of the same duration but with different transition times: 0.6, 1, 1.8, 2.7, or 4.2 ms. The 10 ms duration was chosen larger in order to not interfere with the perception of the sharpness. The same experimental protocol was implemented to discriminate between durations. A reference signal of 0.8 ms duration and 0.5 ms transition time was to be compared with signals having the same transition time but different durations: 1.6, 2.4, 3.2, 4 or 4.8 ms. In both experiments, each pair of stimuli was presented 10 times in a random order for a total number of 50 trials. Participants actively swiped their finger one time across the screen of the tactile display without defined speed or normal load constraints.

4.3 Results

Participants showed a very good capacity to distinguish between signals with differing duration and transition time. When comparing signals of different transition times and durations against the reference stimuli, the 75% JND was estimated for each participant (Fig. 2a) and the median of the individual thresholds was computed for both the duration and the transition time (Fig. 2b). The median JND for transition time was 2.3 ms (IQR = $3.8 - 1.6$) and the median JND for duration was 2.4 ms (IQR = $3.7 - 1.9$). Both thresholds correspond to Weber fractions above 3, which are typically observed for near-threshold intensities [44]. These Weber fractions are very large compared to usual values, which are between 0.1 and 0.3 [45] suggesting that for very small temporal differences, perception is mostly constrained by the limits of human touch mechanical sensitivity (Fig. 2c).

5 Experiment 2: Subjective perception of consecutive signals

5.1 Participants

Six participants, aged between 23 and 32 (1 female), participated in experiment 2. During the psychophysical experiments, participants were wearing active noise-canceling headphones (Quiet Comfort 25, Bose, USA) to prevent potential interference from auditory cues.

5.2 Materials and methods

In experiment 2, participants were asked to count the number of edges that they felt during a tactile exploration of an ultrasonic signal. The ultrasonic signal was always composed by two square reductions of friction that were played at an interval of 300 ms but had different durations (30, 50, 70, 90, 110 ms) and transition times (0.5, 1.2 or 2.0 ms). The range of the displayed stimuli was selected on the basis of preliminary experiments, during which several repetitions of durations from 10 ms to 110 ms were tested by three of the experimenters in order to find the appropriate span of values for the experiment. Each combination of duration and transition time was randomly presented 10 times to the participants (150 trials in total). At each trial, participants explored the signal only once and were forced to report the number of edges that they felt by typing a number between 0 and 6 on a wireless keyboard. As in experiment 1, participants actively swiped their finger across the screen of the tactile display without defined speed or normal load constraints.

5.3 Results

Results showed that for a constant number of delivered square reductions of friction, the number of distinct edges felt by participants was increasing for larger durations (Fig. 3a and Table 1). A statistically significant increase of the number of felt edges between 30 ms and 110 ms of duration was observed for each of the tested transition times (paired t-test with Bonferroni correction: $p < 0.5$ for the three tested transition times). A matched-pairs signed rank Wilcoxon test across the three conditions confirmed a strongly significant increase in the number of perceived edges (n = 18, $p < 0.0001$). At 30 ms, participants felt two edges most of the time and no significant deviation was observed (t-test against two with p = 0.73 p= 0.17 and p= 0.43) while at 110 ms, the answers were significantly larger than two (Bonferroni corrected t-test against two with respectively p = 0.002, p = 0.001 and p = 0.011).

We found that sharpness also significantly affects the increase of the number of perceived edges depending on the transition time (one-way ANOVA: p = 0.012). The results suggest that an increased sharpness of the stepwise frictional transitions would lead to a lower probability of perceiving a larger number of edges during a stimulation by consecutive stimuli. Moreover, it is interesting to notice that for larger durations of the square reductions, the number of reported stimulations is not predominantly 4 but is uniformly distributed between 2, 3 and 4 and participants often reported having felt 3 edges (Fig. 3b). These results suggest that the doubling of the perception is sometimes only felt for one of the two square reductions that are presented to the participant.

6 Experiment 3: Characterization of the frictional changes induced by square friction modulation

6.1 Participants

Six participants, aged between 27 and 60 (2 females), participated in experiment 3.

TABLE 2
Characterization of the finger-surface lateral force induced by the ultrasonic modulation (Median and IQR).

	Reduction of Lat. Force (%)		Lat. force rate change for each stepwise transition (N/s)			
	pulse 1	pulse 2	t_1	t_2	t_3	t_4
Slow	16.4 % (25.2−10.6)	12.2 % (20.8−7.8)	15.2 N/s (20.2−9.5)	16.0 N/s (21.4−9.9)	12.6 N/s (18.9−8.3)	11.7 N/s (18.8−7.8)
Fast	6.4 % (13.9−0.0)	15.2 % (22.5−8.9)	13.7 N/s (18.4−8.9)	15.8 N/s (24.9−10.6)	14.8 N/s (23.4−9.3)	7.5 N/s (14.4−3.6)

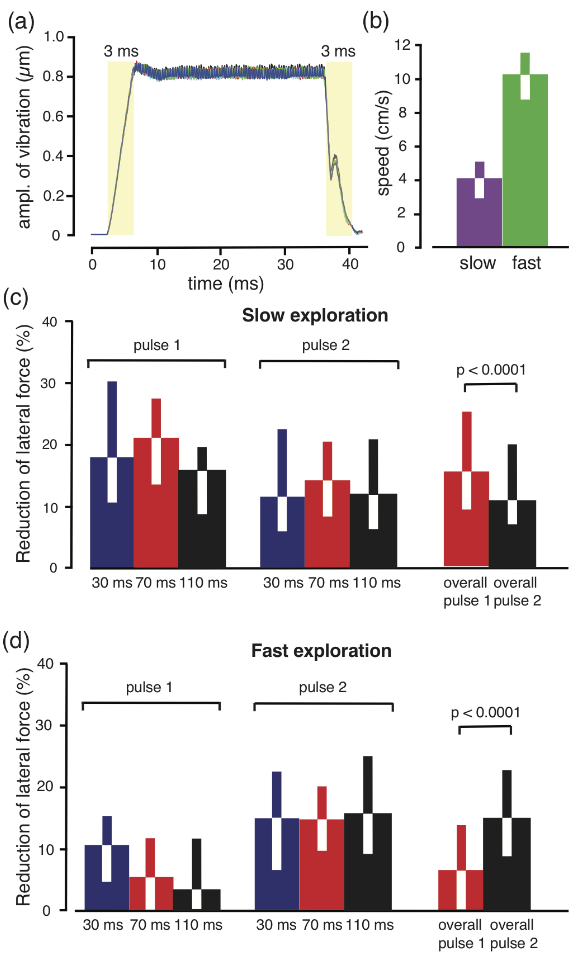

Fig. 4. (a) Examples of the square modulation of the ultrasonic friction when the glass plate from E-ViTa was mounted on the platform for force recording. The ultrasonic stimulation was identical for all delivered pulses throughout the experiment and had a transition time of 3 ms for both the increasing amplitude and the decreasing amplitude. (b) Median and interquartile range of the exploration speed across all trials in the slow and fast speed conditions (c) In the slow speed condition, median and interquartile range of the lateral force reduction for the first and second pulse and all the possible durations: 30 ms, 70 ms and 110 ms (left). The results were also merged and compared between the first and second ultrasonic pulse (right). (d) Identical analysis as in c for the fast exploration condition.

6.2 Materials and methods

In a third experiment, the ultrasonic signal was composed again by two identical square reductions of friction, whose increasing and decreasing transition time was always 3 ms (Fig. 4a) while three durations from experiment 2 were tested (30, 70, 110 ms) and the ultrasonic amplitude was set to 800 nm. The different conditions were counterbalanced and, for each condition, the participants had to perform ten consecutive swipes on the glass surface in the same direction from left to right. At each trial, the stimulation started when the finger reached the middle of the plate. For a trial to be considered successful and recorded, the participant had to maintain the finger-surface normal force between 0.5 N and 2 N throughout the tactile exploration. Feedback about the exerted normal force was provided by a blue led that switched itself on in the desirable force range. Participants were asked to redo the failed trials until successful completion. During this procedure, each trial required a specific calibration of the set-up and when recording the forces, we could not perform a simultaneous psychophysical assessment. We also instructed the participants to swipe their finger on the surface with two different speeds: slow and fast. They were let free to choose the slow and fast speed according to their own preferences.

6.3 Results

6.3.1 *Analysis of the friction reduction induced by the consecutive pulses*

We first verified that the difference between the conditions with instructions to explore slowly or fast was strongly significant (Wilcoxon matched-pairs signed rank test: n = 180, $p < 0.0001$). Participants explored with a median speed of 4.02 cm/s (IQR = 5.00 − 2.81) in the slow condition and 10.25 cm/s (IQR = 11.16 − 8.72) in the fast condition (Fig. 4b).

We then computed the lateral force reduction induced by each square modulation by taking the percentage between the mean lateral force during the 30 ms interval that followed the start of the ultrasonic stimulation and the mean lateral force during the 30 ms pre-stimulation interval (See Table 2). The results showed that although the two ultrasonic square stimulations were identical, they triggered significantly different mechanical responses of the finger for the different speed conditions. For slow tactile exploration, the first pulse was found to induce a stronger reduction of friction than the second one (Wilcoxon matched-pairs signed rank test: n = 180, $p < 0.0001$) (Fig. 4c) while this trend was reversed when the participant explored rapidly (Wilcoxon matched-pairs signed rank test: n = 180, $p < 0.0001$) (Fig. 4d). We also found that the average median of the first pulse during fast exploration was particularly low (6.4 % with IQR = 13.9 − 0.01).

Allowing participants to decide by themselves of the speed of movement in both conditions lead to a wide distribution of the average speed observed across the trials. This wide spread of the speeds enabled us to compute a Spearman correlation analysis between the induced reduction of the lateral force and the mean speed of exploration. We ran separate analyses for the first and second pulses and

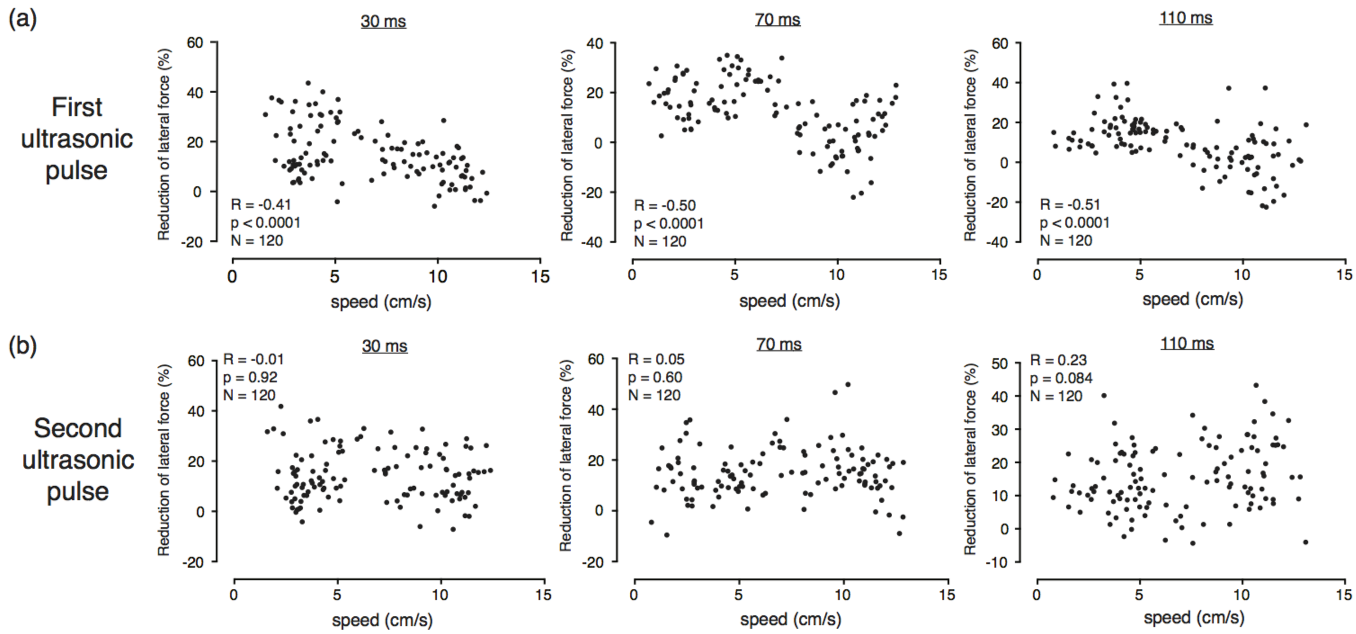

Fig. 5. (a) For all the possible durations (30 ms, 70 ms and 110 ms), Spearman correlation between the speed of exploration and the reduction of lateral force for the first ultrasonic pulse of the trial. (b) For all the possible durations (30 ms, 70 ms and 110 ms), Spearman correlation between the speed of exploration and the reduction of lateral force for the second ultrasonic pulse of the trial.

for all the possible durations of the ultrasonic signals. For each correlation, we had 120 data points: 6 participants x 10 trials x 2 speed conditions. The correlation between speed and reduction of the lateral force (Fig. 5a) was strongly significant for the first of the two ultrasonic pulses (Spearman correlation statistics with Bonferroni correction are: R = -0.41, $p < 0.0001$ for 30 ms; R = -0.50, $p < 0.0001$ for 70 ms; R = -0.51, $p < 0.0001$ for 110 ms; N = 120 in all conditions). On the other hand, we found no correlation between the speed of exploration and the reduction of the lateral force for the second pulse (Fig. 5b), which was presented 300 ms after the start of the first one (Spearman correlation statistics with Bonferroni correction are: R = -0.01, p = 0.92 for 30 ms; R = 0.05, p = 0.60 for 70 ms; R = 0.23, p = 0.084 for 110 ms; N = 120 in all conditions). Thus, a higher exploration speed significantly decreased the saliency of the first ultrasonic square stimulation while it had no effect on the second one.

6.3.2 Analysis of the sharpness of the frictional stepwise transitions

The sharpness of the frictional transitions experienced by the participants is mostly conveyed by the rate of change of the lateral force on their fingertip during the stimulation. Thus, we computed the first derivative of the lateral force for each trial to estimate the sharpness of the four frictional transitions induced by the consecutive pulses (Fig. 6a). In both the fast and slow condition, we found an effect of the transition's position (t_1, t_2, t_3 or t_4) (Friedman test with respectively n = 180, Q(4) = 20.86, p = 0.0001 for the slow condition and n = 180, Q(4) = 133.8, $p < 0.0001$ for the fast condition) with the data suggesting a reduced sharpness for the transitions related to the second pulse (See table 2). This effect was the strongest on the last transition t_4 when participants were instructed to perform a fast exploration (Wilcoxon matched-pairs signed rank test against t_1, t_2 and t_3: $p < 0.0001$ in all cases) (Fig. 6b). Thus, in both speed conditions, the sharpness of the frictional transitions tended to be higher for the first pulse and the sharpness of the frictional recovery from the second ultrasonic pulse was especially low during fast exploratory movement.

7 Discussion

Our results show that touch is very sensitive to the duration and sharpness (transition time) of short square ultrasonic pulses, which are in the range of a few milliseconds. Considering that a 2.4 ms temporal differences requires a minimal sampling rate of 833 Hz to be encoded (Shannon-Nyquist theorem), these results also show that humans can use the full extent of their mechanoreceptors bandwidth to distinguish tiny differences between ultrasonic reductions of friction. These results further raise the question of the neural mechanisms mediating tactile perception of longer and more complex signals. In the second experiment of this study, square reductions larger than 70 ms tend to be felt as two distinct signals probably because the participants perceived the two stepwise transients. This threshold is astonishingly large compared to the results of the first experiment and might be due to the stronger saliency of the stepwise rising friction compared to stepwise falling friction, which was recently shown for single step transitions [15]. It is possible that the more salient frictional transition masks the less salient one when the duration of the square signal is shorter. There is also the possibility that the interval between the two pulses would influence their perception. However, the smallest interval between the end of the first signal and the beginning of the second was 190 ms, which is larger than the time scale at which the doubling phenomenon occurred

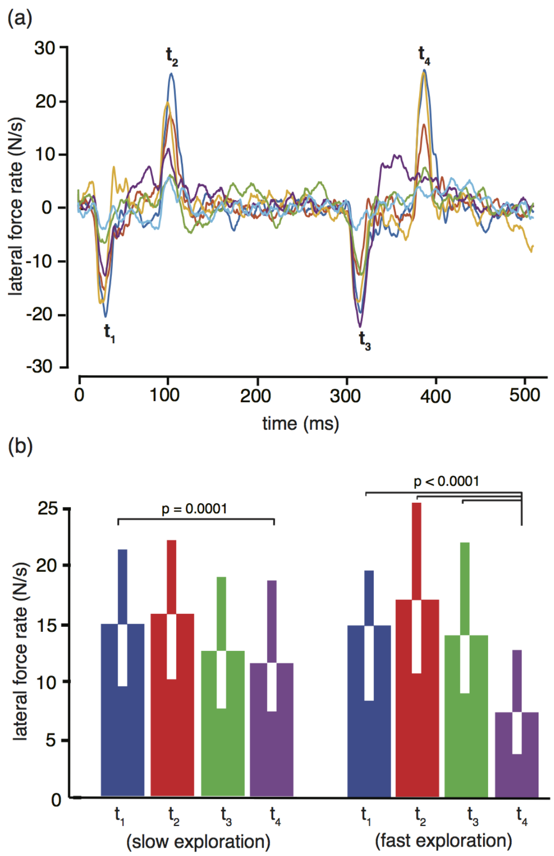

Fig. 6. (a) One example per participant chosen from the slow exploration of consecutive ultrasonic square signals of 70 ms duration. t_1, t_2, t_3 and t_4 represent the four peak changes in the lateral force induced by the ultrasonic step transitions. (b) For each of the four transitions, the peak rate of change of the lateral force was computed across all the trials of the experiment (Median $\pm$ IQR). The computation was respectively performed for the slow exploration (left) and the fast exploration (right).

and makes this type of interference unlikely. Nevertheless, it might be interesting to test various inter-stimulus intervals in future work.

The perception of real or virtual edges depends on the shear forces that apply to the contact area of the fingertip, on their encoding by the tactile mechanoreceptors and on their subjective perception by the higher cognitive areas. The contact force measurements performed in experiment three showed that although the ultrasonic signals were fully reproducible and identical for the two consecutive pulses of a trial, the frictional changes that they generated depended on the speed of exploration and on the position of the pulse within the pattern (first or second). We found the median exploration speeds to be around 4 cm/s when we instructed participants to explore slowly and 10 cm/s when they had to explore fast, which is in the lower range of typical unconstrained speed of exploration (from 5 to 20 cm/s) [46]. Our slow condition corresponds to the slowest tactile interactions that a user would perform on a tactile device while the fast condition would be typical of most tactile interactions on a smartphone.

Our measurements of the contact forces showed that the exploratory speed conditions had a major influence on the frictional dynamics induced by the square ultrasonic stimulations. A recent study showed a higher frictional contract for very slow exploration (0.5 cm/s) compared to a 2 cm/s speed [11] in passive touch conditions. Our results show indeed a strong correlation between the reduction of friction and the speed of exploration for the first of the two square stimulations but no such correlation is observed for the second one. This difference between two identical signals is surprising and suggests that the mechanical characteristics of the finger vary between pulse 1 and pulse 2. This phenomenon could also have a perceptual influence. A recent study estimated the 75% just noticeable difference for such stimuli to be 11% [10], which implies that in many trials performed with a fast speed, the first pulse may be barely noticeable or undetected while the second one is largely above the perceptual threshold.

In our set-up, the ultrasonic stimulation started when the finger reached the middle of the surface. Thus, for a fast finger movement, the ultrasonic stimulation started sooner after the onset of the tactile exploration. There is evidence that stable contact between the finger and the surface takes time to build [47] and that specific phenomena such as partial slip of the finger-surface contact area take place at the start of the sliding [48]. These results suggest that the onset dynamics of the sliding finger are influenced by its speed and that their characteristics for fast speed interfere with the frictional reduction induced by stepwise ultrasonic stimulation.

The rate of change of the lateral force at the transitions t_1, t_2, t_3 and t_4 also showed different dynamics for the two ultrasonic pulses. The transitions induced by the second pulse tended to be less sharp than those induced by the first one. In the slow condition, the differences between the four transitions were small and probably unnoticeable. However, the reduction of sharpness was particularly salient for the last transition of the second pulse during fast exploration. This difference suggests the possibility that participants would not report this transition as an edge, which might also explain the frequent reporting of three perceived edges by participants.

8 Conclusion

Square modulations of friction cannot be expected to recreate the rendering of complex textures such as fabrics or wood but they are especially salient [14] and typically used to create the feeling of edges or gratings on the screen of tactile displays [49]. Their simplicity of implementation also makes square signals practical for commercial uses. For example, the Haptic Creation Tool developed for the Xplore Touch ultrasonic device (Hap2U, France) provides ultrasonic square modulation with variable intensity and sharpness to create distinguishable haptic surfaces in specific areas of the screen. In such applications, it is essential to deliver stimuli that will be felt unambiguously. For example, a 1cm wide ultrasonic square modulation on the screen with the typical speed of exploration could last from 40 ms to 120 ms in the temporal domain, which is typically the range of durations for which the perceptual ambiguity is strongest between the possible numbers of perceived edges. The potentially ambiguous perception of tactile features could provide the user with a misleading and frustrating tactile feedback. Thus, the knowledge of the boundary conditions for which a frictional signal can be perceived only as one type of percept is very important for the future research on friction-based virtual tactile textures.

In addition, our results suggest that ultrasonic friction modulation should adapt the ultrasonic intensity of haptic features to the starting point and speed of the exploratory motion to produce identical frictional dynamics of the ultrasonic stimulation for consecutive variable tactile explorations. This is particularly true on smartphones where slidings on the screen are short and the haptic feedback is delivered shortly after the onset of the tactile motion. Moreover, the implication of the influence of these parameters probably reaches beyond the perception of square reductions of friction since fast exploration strongly reduced the ultrasonic friction modulation for the first pulse. This drastic effect on the capacity of the ultrasonic stimulation to reduce friction suggests that, at the onset of movement, a decrease in the amplitude of the ultrasonic friction reduction is possible for all types of stimuli (edges, textures, geometric shapes,etc). To that end, tactile exploration of a set of signals with a wide range of profiles should be performed. Our future work will focus on simultaneous psychophysical and contact force recordings with precise characterization of the onset of the tactile exploration to better understand how the behavioral and mechanical parameters shape tactile perception of ultrasonically induced frictional patterns.

ACKNOWLEDGMENT

This work was supported by the FP7 Marie Curie Initial Training Network PROTOTOUCH, grant agreement No. 317100, by the MATRICE project (ERDF / Région Nord-Pas-de-Calais-Picardie, France) and by the IRCICA research institute. The authors would like to thank Michel Amberg who prepared and calibrated the ultrasonic tactile set-ups used in this study.

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